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Title

Method and apparatus for stabilizing a glow discharge
plasma under atmospheric conditions.

Field of the Invention

The present invention relates generally to a method and an
apparatus for generating a glow discharge plasma under atmospheric
pressure conditions and, more specifically, to a method and an apparatus
for stabilizing such a glow discharge plasma.

Background of the Invention

Atmospheric Pressure Glow (APG) discharge is used in
practice, among others, for non-destructive material surface
modification. Glow discharge plasmas are relatively low power density
plasmas, typically generated under atmospheric pressure conditions or
partial vacuum environments.

Most commonly, the plasma is generated in a plasma chamber
or plasma discharge space between two oppositely arranged parallel plate
electrodes. However, the plasma may also be generated using other
electrode configurations such as, for example, adjacently arranged
electrodes. The plasma is generated in a gas or a gas mixture by
energizing the electrodes from AC power supply means.

It has been observed that a stable and uniform plasma can
be generated in, for example, a pure Helium or a pure Nitrogen gas.
However, as soon as impurities or other gasses or chemical compositions
at ppm level are present in the gas, the stability of the plasma will
decrease significantly. Typical examples of stability destroying
components are O_2, NO, CO_2, etc..

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Instabilities in the plasma will either develop in a high current density plasma or will extinguish the plasma locally. With a large density of species and a high frequency of collisions in the plasma, an APG shows a fast positive feedback. That is, a random local increase of the ionization of the plasma will exponentially increase. Accordingly, an instability will develop either in a high current density plasma or will extinguish locally the plasma. This phenomenon of exponential increase of the plasma current is known as glow to arc transition. As a result, current arcing occurs and the glow discharge plasma can not be maintained. Instead, a combination of filamentary - and glow discharge is generated.

Filamentary discharge between parallel plate electrodes in air under atmospheric pressure has been used to generate ozone in large quantities. However, filamentary discharge is of limited use for surface treatment of materials, since the plasma filaments tend to puncture or treat the surface unevenly and are associated with relatively high plasma current densities.

Summary of the Invention

It is an object of the present invention to provide a novel and improved method and apparatus for preventing glow to arc transition in an atmospheric glow discharge plasma.

This and other objects and features are achieved, according to the present invention, by a method for controlling a glow discharge plasma in a gas or gas mixture under atmospheric conditions, in a plasma discharge space comprising at least two spaced electrodes, wherein at least one plasma pulse is generated by applying an AC plasma energizing voltage to said electrodes causing a plasma current and a displacement current, said at least one plasma pulse comprising an absolute pulse maximum, characterized in that, said method comprises the step of

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controlling said energizing voltage such that a relative decrease of said displacement current is provided before said pulse maximum.

As we are dealing with an alternating energizing voltage, the sign of the amplitude thereof and also of the displacement current will change from positive to negative. In the case of the positive half cycle or period of the energizing voltage, a decrease of the displacement current will reduce the probability of filament formation. A displacement current having a negative value will not allow the formation of any filaments. Consequently one can prevent the generation of the filaments by sharply decreasing the displacement current during the plasma generation before the pulse maximum, in accordance with the present invention.

In the case of the negative half cycle of the energizing voltage a similar explanation, but with opposite signs as mentioned above, is valid.

For clarity purposes, the term "sharp relative decrease" of the displacement current has to be construed in that the word "sharp" indicates that there is a rapid change of the displacement current, while "relative decrease" means that the sign of the changes can be positive as well as negative. In case the energizing voltage is in the positive half cycle, the "sharp relative decrease" of the displacement current means that the displacement current decreases rapidly going to zero or even a negative value. If the energizing voltage is in the negative half cycle, the "sharp relative decrease" of the displacement current means that the displacement current increases rapidly going to zero or even a positive value.

Unless it is mentioned otherwise below, the description of the processes and/or measures to stabilize the glow plasma in accordance with the invention is mainly provided for the positive half cycle of the displacement current. An identical description for the negative half cycle of the displacement current can be equally provided by changing the

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sign to the opposite. Hence for the negative half cycle, the prevention
of filament generation can be achieved, in accordance with the present
invention, by relatively sharply decreasing the displacement current
(corresponding to an absolute increase of the displacement current)
during the plasma generation before the relative pulse maximum
(corresponding to the absolute minimum) of said plasma pulse during the
negative half cycle. For clarity purposes, hereinbelow the invention will
be described in relation to a positive half cycle only, and similar
measures during the negative half cycle with similar effect are to be
assumed, unless stated otherwise.

        In a preferred embodiment of the invention, at least one of
the electrodes is covered by a dielectric material.

        The method according to the present invention is based on
the insight that in a dielectric barrier discharge the density of the
filamentary discharges can be controlled by the displacement current. In
a filamentary discharge, a large quantity of charge is generated and
accumulates on the dielectric which covers the or each electrode. This
results in a substantial drop of the gas voltage in the area where the
filament was generated. A new filament can not be generated in the
neighbourhood of this area until the voltage between the electrodes, and
thereby the gas voltage, is increased. Thus, the displacement current
controls the rate of voltage variation and is proportional with the
density of filamentary discharges per unit of time.

        In order to create a homogenous glow discharge, it has been
found that the relative decrease of the displacement current has to take
place within a time interval, which time interval is of an order of a
microsecond, preferably fractions of a microsecond. The time interval may
for example be within a range of 0.05 µs and 10 µs. Within this short
time interval, the relative decrease of the displacement current is
preferably being at least 100%.

        Additionally, good results have been achieved in an

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embodiment of the invention wherein the relative decrease of the displacement current resulted in a negative value for the displacement current.

It has also been found that when a mixture of glow and filaments is formed, the stability of the glow plasma will not be significantly affected by the decrease of the displacement current.

This phenomenon might be caused by the fact that the current density in the glow plasma is three to four orders of a magnitude smaller than in a filament (streamer). Hence, the energizing voltage drop due to the generation of glow plasma will be three to four orders of magnitude slower than in the filament case. Another factor that may explain the finding is the homogeneity of the glow plasma, where one does not need to re-ignite the plasma periodically as in the case of filaments. Consequently, the sharp decrease of the displacement current during the plasma generation will not affect the glow variety, but will only eliminate the risk of filament formation, as required.

The present invention is therefore most suitable for stabilizing an unstable plasma, which instability may be caused by the properties of the dielectric surface, the use of a low frequency, electron negative gas, and other factors. The method according to the present invention is also very suitable for stabilizing a plasma discharge comprising a mixture of filaments and glow, and for keeping the glow plasma stable by preventing the transition from the glow to the filamentary state.

The gas voltage variation is given by:

$$dV_{gas}/dt = dV_a/dt - I_p/C_{dielectric} \qquad (1)$$

wherein: V_a = energizing or applied voltage

V_{gas} = gas voltage

I_p = plasma current

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$$C_{dielectric} = capacitance\ of\ the\ dielectric\ barriers$$

and the first derivative of the energizing voltage or applied voltage over time is given by:

$$dV_a/dt = I_d/C \qquad\qquad (2)$$

wherein: I_d = displacement current

C = total capacitance of the dielectric barriers and
                    discharge gap

The second derivative of the energizing or applied voltage over time is in fact proportional to the first derivative of the displacement current over time and is given by:

$$d^2V_a/dt^2 = 1/C \cdot dI_d/dt \qquad\qquad (3)$$

and the total current measured in the current path of the plasma electrode, I_t, is given by:

$$I_t = I_p + I_d \qquad\qquad (4)$$

and: $V_a = V_{gas} + V_{dielectric}$ \qquad\qquad (5)

wherein: $V_{dielectric}$ = voltage across the dielectric barriers.

To avoid any instability, the gas voltage variation has to be below zero or close to zero. Thus the maximum value of the displacement current $I_d{}^{max}$ has to be smaller than:

$$I_d{}^{max} \leq C \cdot I_p{}^{max}/C_{dielectric} \qquad\qquad (6)$$

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wherein: I_p^{max} = maximum value of the plasma current.

It will be appreciated that a small displacement current close to zero or below zero will always be below the critical stability limit, whatever the maximum plasma current density or stray or dielectric capacitance will be. Thus, by using the embodiments described in the present invention the glow will be always in a safe region wherein the glow to arc transition risk is small.

The method according to the present invention is also based on the insight that the adverse effects of filamentary discharge in an APG plasma for surface treatment can be reduced by enhancing or stimulating secondary electron emission from the surface by selecting a suitable material with a relatively high secondary electron emission.

In the case that there is a tendency of a generation of local high current density instabilities (plasma filaments), the rate of filament formation is determined by the displacement current or by the time derivative of the energizing voltage. Accordingly, by controlling the second derivative over time of the energizing voltage an effective plasma stability control is achieved.

Based on the above, in a further embodiment of the invention, the displacement current is provided as a first derivative over time of an absolute value of the energizing voltage and wherein the energizing voltage is controlled in a manner such that at plasma generation the first derivative over time of the absolute value of the energizing voltage is sharply decreased.

In accordance with a preferred embodiment of the invention, at plasma generation in the positive half cycle of the energizing voltage, the displacement current is relatively decreased in fractions of a microsecond. Hence, by suddenly decreasing the first derivative over time of the absolute value of the energizing voltage, the required sharp decrease in the displacement current can be obtained both in the positive

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as well as the negative half cycle of the energizing voltage.

That is, with the method according to the present invention, steps are taken from the ignition of a plasma countering instabilities to occur in the plasma, that is in advance. This, different

5 from prior art methods for stabilizing plasma currents which respond to an already occurred plasma instability, i.e. a filamentary current or streamer, as disclosed by U.S. Patent 5,414,324. For protecting the substrate or surface to be treated against sparks, i.e. current arcing in the plasma, an electrically conductive grid is provided between the

10 electrodes. This grid is connected by an inductor having a large inductance. The grid and the inductor operate as a collector of current sparks, which already have occurred in the plasma, and are not operative for preventing the occurrence of such sparks. That is, a spark is already present when the inductor starts to react by decreasing the energizing

15 voltage of the plasma. Note that operation of the grid and the inductor for reducing the energizing voltage is not functional during plasma breakdown. When the plasma develops explosively at breakdown, decrease of the energizing or excitation voltage is not a guarantee that the plasma current will start to decrease. Near breakdown of the plasma, the plasma

20 has a negative resistance, such that the current in fact will increase faster if the voltage is decreased.

In a yet further embodiment of the method according to the invention, the energizing voltage is controlled in a manner such that at plasma generation the second derivative of the energizing voltage over

25 time is proportional and of the opposite sign to the first derivative over time of the plasma current. The stabilization of the displacement current increases significantly the uniformity of the plasma distribution over the surface to be treated, as can be seen in figure 5.

In a yet further embodiment of the method according to the

30 invention, the dielectric material covering at least one of the electrodes should have a secondary electron emission between 0.01 and 1

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and preferably between 0.1 and 1.

If the secondary electron emission is smaller than 0.01, a large volume ionisation coefficient will be required in order to keep a self sustained discharge. As a result of such a large ionisation coefficient, the discharge will develop into a streamer-like discharge. On the other hand, a stable plasma can not be generated at a secondary electron emission higher than 1.

The invention further provides a method for generating plasma, wherein the energizing voltage is controlled in a manner such that the plasma is operated at a voltage just above the breakdown voltage. Preferably, the voltage is a few percent higher than the minimum voltage needed for maintaining the plasma.

The invention provides also an apparatus for controlling a glow discharge plasma in a discharge space having at least two spaced electrodes, means for introducing in said discharge space a gas or gas mixture under atmospheric conditions, a power supply for energizing said electrodes by applying an AC plasma energizing voltage to said electrodes for generating at least one plasma pulse and causing a plasma current and a displacement current, said at least one plasma pulse comprising an absolute pulse maximum, and means for controlling said plasma, characterized in that, said means for controlling said plasma are arranged for controlling said energizing voltage such that a relative decrease of said displacement current is provided before said pulse maximum. At least one of the electrodes is preferably covered by a dielectric material.

In a yet further embodiment of the apparatus according to the invention, the stabilization means are arranged for controlling the energizing voltage in a manner such that at plasma generation the relative decrease of the displacement current is provided in fractions of a microsecond. The stabilization means, comprise pulse generator means providing voltage pulses superimposed at the energizing voltage at the

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electrodes. The pulse generator means are controlled such to that during
plasma generation before the pulse maximum, the second derivate over time
of the absolute value of the energizing voltage has a negative value,
i.e. below zero, preferably a substantially negative value.

5   In another embodiment of the invention, the stabilization
means are arranged for controlling the energizing voltage in a manner
such that at plasma generation the second derivate of the energizing
voltage over time is proportional and of the opposite sign to the first
derivative over time of the plasma current.

10   A suitable pulse generator, for use with the present
invention comprises, in an embodiment thereof, a power amplifier, having
input or control terminals which are connected to means for sensing
plasma current and/or means for providing the first derivative over time
of the displacement current, and wherein the output terminals of the
15   amplifier are connected in series with the power supply means and the
electrodes for superimposing a voltage pulse or voltage pulses at the
plasma energizing voltage.

         Means for generating the first derivative over time of the
displacement current which is able to oppose the plasma current variation
20   can be provided by properly designed inductor means, such as a current
choke coil incorporated in the current path of the plasma discharge
space.

         In an alternative embodiment of the apparatus according to
the invention, the stabilization means comprise inductor means, such as
25   at least one choke coil. At least one of the electrodes and the inductor
means are connected in series to the power supply means.

         During breakdown of the plasma, the plasma current
increases very rapidly, as a result of which a large voltage drop occurs
over the inductor, which is proportional to the rate of change of the
30   current and the inductance of the inductor means. The energizing voltage
applied to the plasma will show a drop having a steep slope. By a proper

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design of the inductor means, the second derivative over time of the absolute value of the energizing voltage will be negative during breakdown of the plasma, i.e. at the rising edge of the plasma current.

5   In a yet further embodiment of the invention the apparatus according to the invention comprises stabilization means having electronic inductor circuitry.

From experimentally obtained data, it has been shown that the method and apparatus according to the present invention results in a very stable plasma from breakdown thereof, for a variety of different

10   supply gases, excitation conditions, electrode designs and electrode spacing, such as a distance from between 0.01 mm to 3 cm.

Gasses for generating the plasma can be selected from a group comprising Helium, Argon, Nitrogen, Air, Oxygen, Carbon Dioxide, Ammonia and a mixture comprising any of the gasses of the group.

15   In a preferred embodiment of the invention, the gas is a mixture of noble gas such as helium or argon and a chemically active gas such as air, oxygen and carbon dioxide. The gasses may also comprise of specific chemical compositions which are usually involved in the chemical vapour deposition processes such as SiH4, hydrocarbons, organosilicons

20   such as Tetraethyl Orthosilicate (TEOS).

The apparatus and method according to the present invention can be used, in practice, for a wide variety of applications such as, but not limited to, a device for plasma surface treatment of a substrate, such as surface activation processes, which substrate can be glass,

25   polymer, metal, etc., and for the generation of hydrophilic or hydrophobic surfaces; a plasma device for a chemical vapour deposition process; a plasma device for decomposition of gasses containing volatile organic compounds; a plasma device for removing toxical compounds from the gas phase; a plasma device for surface cleaning purposes such as in

30   the sterilisation or dry cleaning processes.

The above-mentioned and other features and advantages of

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the invention are illustrated in the following description with reference
to the enclosed drawings.

Brief Description of the Drawings

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        Fig. 1 shows, in a very schematic manner, a commonly known
APG plasma device.
        Fig. 2 shows a graph of the total current waveform and the
energizing voltage waveform in the device of Fig. 1 in Argon, not using
10   the present invention.
        Fig. 3 shows a graph of the total current waveform and the
energizing voltage waveform in the device of Fig. 1 in Argon, using the
present invention.
        Figs. 4 and 5 show fast camera images of surfaces treated
15   in an APG plasma of figs. 2 and 3, respectively.
        Fig. 6 shows, in a very schematic manner, an electric
circuit diagram of an embodiment of the apparatus according to the
present invention.
        Fig. 7 shows, in a very schematic manner, an electric
20   circuit diagram of a further embodiment of the apparatus according to the
present invention.
        Fig. 8 shows a graph of part of the total current waveform
and the energizing voltage waveform in the apparatus of fig. 7.
        Fig. 9 shows a typical I-V characteristic of an unstable
25   plasma discharge, calculated from measured values.
        Fig. 10 is a schematic illustration of an electric circuit
diagram of another embodiment arrangement according to an embodiment of
the present invention.
        Fig. 11 shows the AC energizing voltage, the plasma current
30   and the displacement current of a plasma generated using the embodiment
of fig. 10 of the present invention.

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Detailed Description of the Drawings

Without the intention of limitation, the present invention will now be disclosed in more detail with respect to the attached drawings. In the drawings, like parts are designated by like reference numerals.

Fig. 9 shows a typical plasma current, I_p, vs. gas voltage, V_{gas}, characteristic of an unstable plasma. The gas voltage V_{gas} is depicted in Volts along the horizontal axis and is calculated by subtracting from the applied or energizing voltage V_a the voltage drop $V_{dielectric}$ across the dielectric barriers. The plasma current I_p plotted in mA along the vertical axis is calculated by subtracting the displacement current I_d from the total current I_t running through the system. The current and voltage values provided in Fig. 9 are for reference purposes only. The plasma is characterized by a very low dynamic resistance, thus being very sensitive to any perturbation.

As can be seen from Fig. 9, an increase of the gas voltage V_{gas} to values just above the breakdown voltage (i.e. near ±1000 Volt in this example) will trigger a large plasma current variation I_p and most probably a transition from glow to arc or another filamentary state.

Fig. 1 shows a very schematic embodiment of a commonly known Atmospheric Pressure Glow (APG) plasma apparatus or device 10. The apparatus 10 comprises a plasma chamber or plasma discharge space 11 and means 12 for supplying a gas or a gas mixture under atmospheric pressure conditions in the discharge space 11, indicated by arrow 17. For producing and sustaining a glow discharge plasma in the plasma discharge space 11, for treating a surface 19 of a body 18, at least two oppositely spaced electrodes 13 and 14, in the discharge space 11 connect to AC power supply means 15, preferably AC power means, via an intermediate transformer stage 16. The frequency of said AC power supply means is selected between 10 kHz and 50 MHz.

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Although two oppositely spaced electrodes 13 and 14 at a distance d are shown, the apparatus 10 may comprise a plurality of electrodes, which not necessarily have to be arranged oppositely. The electrodes 13, 14 may be positioned adjacently, for example. At least one

5   of the electrodes is preferably covered by dielectric material having a secondary electron emission between 0.01 and 1.

In accordance with the present invention, adverse effects of filamentary discharge in an APG plasma are reduced by controlling the energizing voltage V_a such that at plasma generation a sharp relative

10   decrease of the displacement current is provided, which is comes down to the case wherein the second derivate over time of the absolute value of the energizing voltage has a value less than zero, and preferably having an as large as possible negative value.

Fig. 2 shows graphically the results of the measured

15   energizing voltage V_a and the total current I_t waveforms in an experimental set up, wherein a plasma is created in Argon in a plasma discharge space as schematically shown in fig. 1. The electrode distance or spacing d=1 mm and the energizing voltage V_a has a frequency of 11.8 kHz. Time t in microsecond is depicted running along the horizontal axis.

20   On the left vertical axis of the graph, current values of I_t in mA are indicated. On the right vertical axis of the graph voltage values of V_a in V are shown.

As can be seen from fig. 2, at plasma breakdown a number of current streamers is generated leading to an unwanted filamentary plasma.

25   Fig. 3 shows, similar to fig. 2, graphically the results of the measured energizing voltage V_a and the total current I_t waveforms in an experimental set up wherein a plasma is created in Argon in a plasma discharge space as schematically shown in fig. 1, however using the measures according to the present invention. The electrode distance or

30   spacing d=1 mm and the energizing voltage V_a has a frequency of 13 kHz.

As can be seen from fig. 3, at plasma breakdown in the

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positive half cycle, that is at or already before the leading edge of the total current I_t, the energizing voltage V_a is arranged to have its second derivative over time less than zero. As a result, no current streamers are generated and a more uniform and stable plasma is created. The plasma

5   is preferably generated at a voltage which is a few percent higher than the minimum voltage for maintaining the plasma.

         The improvement according to the present invention can be further illustrated from pictures taken with a fast image camera of a surface treated in the above-mentioned examples. Fig. 4 shows a surface

10   treated in the set up as disclosed in connection with fig. 2. Fig. 5 shows a surface treated in the set up as disclosed in connection with fig. 3. In figs. 4 and 5, the vertical axis or direction as seen in the plane of the drawing, represents time frames of 30 microseconds and the horizontal axis or direction represents spatial homogeneities of the

15   plasma. Due to the unwanted streamers, the surface of fig. 2 is not evenly treated, which can be clearly seen from the randomly spread perturbations over the surface due to the filamentary discharge plasma generated. The surface shown in fig. 5 is clearly more evenly treated. No perturbations are visible and due to a stable glow plasma generated.

20   In an embodiment of an apparatus 20 according to the invention, stabilization means 21 are provided in the form of a pulse generator, indicated in dashed lines, which generates voltage pulses to modify the voltage provided by the AC power supply means 15, such that at plasma generation the second derivative over time of the energizing

25   voltage V_a is less than zero. The amplitude of the voltage pulses of the pulse generator 21 is opposite to the AC powering voltage of the AC power supply means 15. The pulses generated by the pulse generator 21 may be suitably superimposed on the energizing voltage.

         In an alternative embodiment, the stabilization means 21

30   comprise a pulse generator 22 the input or control terminals 23, 24 of which are connected to current sensing means 25 which connected in series

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with at least one of the electrodes 13 of the plasma discharge space and the AC power supply means 15, i.e. in the total current path. The output terminals 26, 27 of the pulse generator 22 are connected in series with the power supply means 15 and the electrode 14 of the plasma discharge

5   space.

The pulse generator 22 is activated at plasma breakdown, which is sensed by the current sensing means 25. The current sensing means 25 may take several forms, such as but not limited to electronic components, inductor means and/or a small resistor. Breakdown of the

10   plasma can be detected from saturation of inductor means such as a choke coil, for example.

The means 25 additionally may also be arranged, in accordance with a further embodiment of the invention, for providing the first derivative over time of the displacement current dI_d/dt. Means for

15   this purpose may comprise, inter alia, suitably designed inductor means.

In a yet further embodiment of the invention, the means 25 may be arranged for providing the first derivative over time of the energizing voltage dV_a/dt. The pulse generator means 22, at plasma generation, are arranged for suddenly decreasing dV_a/dt, generating a

20   large and negative second derivative over time of the energizing voltage. i.e. $d^2V_a/dt^2 \ll 0$.

Effective plasma stabilization is achieved if at plasma generation the second derivate of the voltage over time is negative, $d^2V_a/dt^2 < 0$, and its absolute value is proportional to the first

25   derivative over time of the displacement current dI_d/dt.

Pulse generator means 22 and means 25 for current sensing and/or for providing derivatives of electric quantities are known to the skilled person and, for the purpose of the present invention, need no detailed explanation here.

30   Fig. 7 shows a simple embodiment of an apparatus 30 according to the invention, using inductor means 29 connected in series

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with the power supply means 15. The inductor means 29 may comprise suitably designed choke coil means or electronic inductor means. The inductor means are designed such to modify the supply voltage provided by the supply voltage means 15 to provide an energizing voltage V_a at the
5   electrodes 13, 14 having a second derivative over time less than zero.

Fig. 8 shows part of the measured energizing voltage V_a and the total current I_t waveforms in an experimental set up, using the apparatus shown in fig. 7 with Ar gas and an electrode spacing of 1 mm.

As indicated by reference numeral 35, at the leading edge
10   of the total current I_t, due to the operation of the inductor means 29, the energizing voltage V_a shows a behaviour equal to a voltage of which the second derivative over time is less than zero. As a result, a very stable plasma is generated, without streamers.

Figure 10 is a schematic illustration of an arrangement
15   according to an embodiment of the present invention, wherein an AC power supply 41 is connected to an electrode configuration 42 forming a discharge space for generating an Atmospheric Pressure Glow (APG) plasma. In series with the electrode configuration 42, there is connected a non-linear electric circuit element in the form of a choke coil 43, which is
20   operated in a saturated state at least during a plasma pulse generated using the AC power supply 41 and in particular in the period of the life cycle of the plasma after its pulse maximum, i.e. at or near the end of the pulse.

In series with the choke coil 43, in accordance with an
25   embodiment of the invention, a further inductor or matching coil 44 is installed which is operated in an unsaturated state. The matching coil 44 is primarily used as phase shifting means, and may be suitably dimensioned for this purpose. In one embodiment, a matching coil having an inductance of 0.7 mH was used together with a ferrite choke coil 43
30   having an inductance between 0.1 and 0.2 mH. The ferrite used in this choke coil is a 3S4 ferrite (MnZn) with $\mu r=1700$, Hc=20 A/m, Br=170 A/m

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and Bsat=350 A/m.

The matching coil 44 also provides a relative decrease of the displacement current in the early stage of the plasma pulse generated using the arrangement of figure 10. This is due to the fact that the matching coil will counteract the rapidly changing magnetic flux during plasma generation before the pulse maximum by responding with a relative decrease of the displacement current (Lenz law). Any instabilities in the plasma will be extinguished as a result of the decreasing displacement current, in accordance with the invention.

A capacitance 45 is parallel connected to the electrode configuration 42 for damping of harmonics. This capacitance 45 may be inherently formed by the stray capacitance of the electrode configuration 42, for example.

The effects of the choke coil 43 may be noted best if the saturation current of the choke coil 43 is at least smaller than the displacement current of the circuit of Figure 10 without a choke coil 43, which is equal to:

$$I_{d, \text{ without\_choke}} = \omega\ C\ V_{max} \qquad\qquad (2)$$

wherein:

ω = fundamental angular frequency of the AC energizing voltage,

C = capacity of the APG electrode configuration, and

V_{max} = amplitude of the AC energizing voltage.

Preferably, the saturation current of the choke coil used is larger than 50% of the displacement current.

Figure 11 shows a graph of the energizing voltage V, the plasma current I_p and the displacement current I_d over time t, in an embodiment of the method of the present invention with the arrangement shown in figure 10. For illustrative purposes, only the positive first halve of the energizing voltage V is shown. A plasma was generated

according to the invention under the following conditions: An LC series network at 240 kHz was used with a resonance or matching coil 44 having an inductance of 2 mH, an APG electrode capacitance 45 of 140 pF, a choke coil 43 having an inductance of 0.7 mH, and with I_d/I_{sat} = 1.4. The gas used was Ar+20% air at atmospheric pressure. To prevent the risk of sparking and for matching reasons a pulsed plasma with a duty cycle of 10% was used.

It can be seen that a plasma pulse 57 is generated having an absolute pulse maximum 58. After the pulse maximum 58, i.e. between time t of approximately 2 and 3 µs, the plasma current I_p decreases, showing a negative slope 59. In accordance with the present invention, in relation to the decrease 59 of the plasma current I_p, a relative decrease 60 of the displacement current I_d occurs, caused by the saturated choke 43. As a result, the plasma current I_p shows a relatively clean downward slope 61, without sharp peaks or spikes generated by plasma filaments, providing a stable glow plasma as intended. For illustrative purposes, the broken line 62 illustrates the plasma current I_p in accordance with the prior art, i.e. without the teachings of the invention. One can observe a very irregular current waveform 62, causing unwanted streamers and the like in the plasma.

From Figure 11 it can be further seen that in the time period at least from just before the plasma breakdown until during the plasma pulse 57 after the pulse maximum 58, the ratio between the displacement current I_d and the saturation current I_{sat} of the choke coil 43 is comprised in a range between 1.2 and 1.6. With this ratio, the displacement current I_d has a substantially triangular shape, except for the regions where the plasma is generated, and shows a relative decrease during the whole of the period from before the start of the plasma pulse 57, after the pulse maximum 58, until the plasma is fully extinguished. This triangular wave form is very beneficial for obtaining a stable plasma breakdown. In general, the stability of the plasma is enhanced by

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steepening the slope of the displacement current, i.e. dI_d/dt.

From Figure 11 it can also be observed that at the generation of the plasma pulse 57, that is before the pulse maximum 58 the displacement current I_d at first drops considerably, i.e. between time t of approximately 1 and 2 µs, indicated by reference numeral 63. This drop 63 of the displacement current I_d is caused by the (unsaturated) matching coil 44. Accordingly, in an arrangement of the invention as illustratively shown in figures 10, amongst others, by properly selecting the choke coil such that ratio between the displacement current I_d and the saturation current I_{sat} of the choke coil 43 is comprised in a range between 1.0 and 3, and preferably between 1.2 and 1.6, in combination with an (unsaturated) matching coil, a sharp relative decrease of the displacement current I_d at the generation of the plasma pulse 57 can be obtained, enhancing and sustaining the generation of a stable glow plasma.

It has been observed that by increasing the ratio between the displacement current I_d and the saturation current I_{sat} of the choke coil 43 beyond 1.6, the voltage over the APG electrodes will show a more rectangular shaped waveform.

From Figure 11 it will be clear that the relative decrease of the displacement current according to the invention and described above is provided in fractions of a microsecond.

Those skilled in the art will appreciate that similar waveforms of opposite sign will occur at the negative halve period of the energizing voltage V.

Although in the above oppositely positioned electrodes have been discussed and shown in the relevant figures, the invention may also be practised with adjacently arranged electrode pairs or other configurations of electrodes of an APG apparatus.

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Those skilled in the art will appreciate that many modifications and additions can be made without departing from the novel and inventive scope of the invention as defined in the appending claims.